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Committee on Science, Space and Technology

Committee Hearing on
"Lessons learned from the Texas blackouts: Research needs for a secure and resilient grid"
March 18, 2021

Testimony

Introduction

Good morning, Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee.

My name is Susan Tierney.[1] I am a Senior Advisor at Analysis Group, an economic consulting firm where I specialize on policy, regulation, economics, environmental, and innovation issues associated with the electric and gas industries.

Thank you for inviting me to testify at this important hearing aimed at discovering what caused the recent extended power outages in Texas during a severe winter storm in mid-February of 2021, and identifying critical research and development needs for grid resilience, reliability and security. I understand that you are particularly interested in research sponsored by the Department of Energy related to relevant grid technology, energy generation technology and cybersecurity research.

I further understand that this hearing serves as a legislative hearing for a bill — Grid Security Research and Development Act (H.R. 5760 in the 116th Congress), which was previously introduced by Representative Ami Bera — expected to be reintroduced in this Congress. That bill would authorize an interagency research, development, and demonstration program on electric-grid and energy-system cybersecurity, physical security, resilience, and emergency response.

I am testifying on my own behalf at today's hearing and it is an honor to share my thoughts and observations with you. But as part of my testimony, I will also share various research-related recommendations of several recent committees of the National Academies of Sciences, Engineering and Medicine ("The Academies") on which I have recently (or currently) served.[2] The recommendations from those committees' reports that I describe in this testimony are ones that relate to resilience, grid modernization and planning, and cyber security. I will be careful to identify those instances where I am reporting the consensus results of those committees versus expressing my own opinion. All of the

[1] I have provided my bio at the end of this testimony.
[2] These three Academies committees on which I have served and whose recommendations I discuss in this testimony are:
- Enhancing the Resilience of the Nation's Electric System (2017), https://www.nap.edu/catalog/24836/enhancing-the-resilience-of-the-nations-electricity-system.
- The Future of Electric Power in the U.S. (2021), https://www.nationalacademies.org/our-work/the-future-of-electric-power-in-the-us;
- Accelerating the Decarbonization in the United States: Technology, Policy and Societal Dimensions (2021). https://www.nationalacademies.org/our-work/accelerating-decarbonization-in-the-united-states-technology-policy-and-societal-dimensions.

National Academies' reports from which I will draw recommendations were completed prior to the Texas events that have prompted this hearing.

The February 2021 outages in Texas led to extremely challenging living conditions for households, including long periods without power and in some cases also without access to other critical services (like water supply) in parts of the state. In holding this hearing, the Science Committee is examining important issues: What led to these events? And what research is needed to avoid or at least minimize the impacts of such events in the future?

The February 2021 Texas electricity crisis highlights the extraordinarily important role that reliable and resilient electric service plays in the economic and social health and well-being of American communities.

It is clear that steps could have been taken by state officials, grid operators and energy asset owners in Texas that would have at least lessened the extent of power system and gas system outages, and the human hardships that resulted from them.

The events also cry out for the need for further research and analysis (not to mention policy and system changes) to ensure reliable and resilient electric supply in the future, even in the event of extreme weather conditions that we can anticipate in the decades ahead. The federal government has an essential role to play in supporting this research. As the Academies' 2017 report on Enhancing the Resilience of the Electric Grid pointed out:

> The Department of Energy (DOE) is the federal entity with a mission to focus on the *longer-term* issues of developing and promulgating technologies and strategies to increase the resilience and modernization of the electric grid. No other entity in the United States has the mission to support such work, which is critical as the electricity system goes through the transformational changes described in this report. The committee views research, development, and demonstration activities that support reliable and resilient electricity systems to constitute a public good. If funding is not provided by the federal government, the committee is concerned that this gap would not be filled either by states or by the private sector. In part this is because the challenges and solutions to ensuring grid resilience are complex, span state and even national boundaries, and occur on time scales that do not align with business models.[3]

I appreciate the Science Committee's attention to these important research questions.

In my testimony, I first discuss the factors that affected the electricity outages that occurred in parts of Texas for several days in February 2021. In this part of my testimony, I draw upon my own experience and understanding of what transpired there. When I turn to the second part of my testimony—where I discuss related research needs for a robust, reliable, safe, and resilient electric system—I draw more directly on the work of the National Academies' committees on which I served.

Factors affecting the electric supply outages in Texas in February 2021:

Much has already been written and said about the Texas electricity crisis, the related public health and safety concerns (and tragedies), and exorbitant electricity price increases in the portion of Texas where the Electric Reliability Council of Texas ("ERCOT) manages the grid and wholesale power market.

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[3] National Academies of Sciences, Engineering, and Medicine, *Enhancing the Resilience of the Nation's Electricity System*, 2017 (hereafter referred to as "Academies' 2017 Resiliency Report"), at https://doi.org/10.17226/24836.

There have already been numerous federal and state legislative and regulatory hearings;[4] bills introduced in Congress[5]; lawsuits;[6] and investigations.[7] Experts are weighing in to explain these events in seminars[8] and podcasts[9], in magazine,[10] newspaper[11] and industry articles,[12] and in other many other commentaries.[13]

Given the extensive coverage of the 2021 Texas electricity crisis, I will just briefly summarize here some of the important pre-existing conditions in the ERCOT electric system, key developments that occurred

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[4] For example: Senate Energy and Natural Resources, Full Committee Hearing on Reliability, Resiliency, And Affordability of Electric Service, March 11, 2021, at https://www.energy.senate.gov/hearings/2021/3/full-committee-hearing-on-the-reliability-resiliency-and-affordability-of-electric-service; Texas Legislature - Joint Hearing of State Affairs and Energy Resources Committees, February 25, 2021, at https://www.youtube.com/watch?v=bmFkAdEAcS0.

[5] See: the Disaster Safe Power Grid Act, sponsored by Senators Wyden and Merkley, at https://www.wyden.senate.gov/imo/media/doc/Disaster%20Safe%20Power%20Grid%20Act%20of%202021%20Bill%20Text.pdf.

[6] Examples: CPS Energy v. ERCOT, March 12, 2021, as described in Brendon Gibbons, "CPS Energy sues ERCOT, alleging 'one of the largest illegal wealth transfers in the history of Texas,'" San Antonio Report, March 12, 2021, at https://sanantonioreport.org/cps-energy-sues-ercot/; The State of Texas v. Griddy Energy LLC and Griddy Holdings LLC, https://www.texasattorneygeneral.gov/sites/default/files/images/admin/2021/Press/01_Griddy%20Petition_2.28.21%20file%20stamped.pdf, as described in Attorney General Kenneth Paxton press release, March 1, 2021, at https://www.texasattorneygeneral.gov/news/releases/ag-paxton-sues-griddy-llc-energy-company-customers-hit-exorbitant-energy-bills.

[7] For example: Federal Energy Regulatory Commission News Release, "FERC, NERC to Open Joint Inquiry into 2021 Cold Weather Grid Operations," February 16, 2021, at https://www.ferc.gov/news-events/news/ferc-nerc-open-joint-inquiry-2021-cold-weather-grid-operations; FERC News Release, "FERC to Examine Potential Wrongdoing in Markets During Recent Cold Snap," February 22, 2021, at https://www.ferc.gov/news-events/news/ferc-examine-potential-wrongdoing-markets-during-recent-cold-snap; Garrett Hering, "In the wake of the storm, Texas PUC opens probe into outages," S&P Global Market Intelligence, February 19, 2021, at https://platform.marketintelligence.spglobal.com/web/client?auth=inherit&overridecdc=1&#news/article?KeyProductLinkType=2&id=62768135.

[8] For example: International Association of Energy Economists; Keystone Energy Board.

[9] For example: Columbia University Center for Global Energy Policy ("Making Sense of the Texas Energy Crisis," February 22, 2021, at https://www.energypolicy.columbia.edu/making-sense-texas-energy-crisis); RFF Resources Radio ("Shedding Light on Electricity Blackouts, with Severin Bornstein," February 23, 2021, at https://www.resources.org/resources-radio/shedding-light-on-electricity-blackouts-with-severin-borenstein/); RFF Resources Radio ("Illuminating the Future of Electric Power in the United States, with Karen Palmer," March 9, 2021, https://www.resources.org/resources-radio/illuminating-the-future-of-electric-power-in-the-united-states-with-karen-palmer)/; Volts (David Roberts, "Lessons from the Texas mess," February 23, 2021, at https://www.volts.wtf/p/lessons-from-the-texas-mess).

[10] For example: Robinson Meyer, "Texas Failed Because It Did Not Plan," *The Atlantic*, February 21, 2021, at https://www.theatlantic.com/technology/archive/2021/02/what-went-wrong-texas/618104/?utm_source=newsletter&utm_medium=email&utm_campaign=atlantic-weekly-newsletter&utm_content=20210221&silverid-ref=MzEwMTkwMjQxOTU4S0.

[11] For example: Katherine Blunt and Russell Gold, "The Texas Freeze: Why the Power Grid Failed," *The Wall Street Journal*, February 19, 2021, at https://www.wsj.com/articles/texas-freeze-power-grid-failure-electricity-market-incentives-11613777856; Russell Gold and Katherine Blunt, "Texas Grapples with Crushing Power Bills After Freeze," *The Wall Street Journal*, February 23, 2021, at https://www.wsj.com/articles/texas-grapples-with-crushing-power-bills-after-freeze-11614095953; Russell Gold and Katherine Blunt, "Amid Blackouts, Texas Scrapped Its Power Market and Raised Prices. It Didn't Work," *The Wall Street Journal*, February 25, 2021, at https://www.wsj.com/articles/texas-power-regulators-decision-to-raise-prices-in-freeze-generates-criticism-11614268158.

[12] For example: Alex Gilbert and Morgan Bazillian, "The Texas electricity crisis and the energy transition," *Utility Dive*, February 19, 2021, at https://www.utilitydive.com/news/the-texas-electricity-crisis-and-the-energy-transition/595315; Molly Christian, Zack Hale and Ellie Potter, "Experts mull market, reliability rule changes amid Texas, regional outages," *S&P Global Market Intelligence*, February 16, 2021, at https://platform.marketintelligence.spglobal.com/web/client?auth=inherit&overridecdc=1&#news/article?KeyProductLinkType=2&id=62688009; Edward Klump, "Texas Blackouts: 10 ways to fix the grid," E&E News, at https://www.eenews.net/stories/1063727199.

[13] For example: Jay Apt and Luke Lavin, "Opinion: What is happening in Texas will keep happening until we take action," *Washington Post*, February 18, 2021, at https://www.washingtonpost.com/opinions/2021/02/18/texas-power-grid-failure-weather/; Carl Pechman and Elliott Nethercutt, "Regulatory Questions Engendered by the Texas Energy Crisis of 2021," NRRI Insights, March 2021, at https://pubs.naruc.org/pub/2AF1F2F3-155D-0A36-3107-99FCBC9A701C; Peter Cramton, "Ten myths of the 2021 Texas electricity crisis and ten steps to avoid a repeat," March 8, 2021.

in tandem as part of the electric crisis, and some of the key conditions and impacts associated with the electrical outages in the ERCOT Texas region.

Pre-existing conditions before the mid-February events

- The ERCOT electric system is one of the largest integrated electric grids around the world, even though it is electrically separated from the rest of the power systems in the lower 48 states in the U.S. From a physical point of view, the ERCOT system includes vast networks of high-voltage transmission lines and a diverse set of power plants (including nuclear, coal, natural gas, and renewable facilities). Sales of electricity to Texas consumers account for 11 percent of the nation's total retail sales.[14]

- For nearly two decades, electricity supply to consumers in the ERCOT portion of Texas has been supplied through restructured, competitive wholesale and retail electricity markets. ERCOT administers the wholesale power market, with oversight by the Public Utility Commission of Texas ("PUCT"). (The Federal Energy Regulatory Commission ("FERC") does not have jurisdiction over wholesale sales in ERCOT because there are no sales in interstate commerce, in light of ERCOT being electricity isolated from other states.) The PUCT has approved a market design for ERCOT's system market that includes the "gold standard" — an approach called a "bid-based, security-constrained economic dispatch with locational marginal pricing" — for determining the pricing and efficient dispatch of electricity resources on the system. Unlike every other region in the U.S. with a centralized grid operator like ERCOT, however, Texas has neither a mandatory centralized capacity market administered by the grid operator (as in the 13-state PJM region, or in New York or New England) nor a state-supervised least-cost resource planning process (as in California, and in the states that participate in the MISO and SPP regions in the central part of the U.S.) in order to ensure that adequate supplies of electrical resources exist on the system. The PUCT has approved this "energy-only market" approach for the ERCOT region, relying on the role of price spikes during periods of electricity shortages to create incentives for investment so that generating resources are available to produce power during those periods.

- The PUCT also oversees the retail electricity market in the service territories of investor-owned utilities. In the ERCOT portion of Texas (i.e., in most of Texas), each electricity customer must choose his/her preferred competitive retail supplier (called Retail Electricity Providers), with power delivered over wires owned by electric utilities).[15] Retail Electricity Providers offer a variety of types of service and price options to customers, including ones with fixed prices over a pre-established contract period and others with prices that vary according to prices that change in the hourly wholesale markets.

- Texas is the only state with this particular combination of elements in its electric industry: a restructured, energy-only wholesale market; and mandatory consumer choice of competitive power suppliers. Largely viewed by academic economists and many—but not all—industry experts as a

[14] Data for 2019 from U.S. Energy Information Administration, State Electricity Profiles, https://www.eia.gov/electricity/state/.
[15] Although retail choice is mandatory for electricity customers of investor-owned utilities, it is only available to customers of municipal and cooperative utilities if the utility opts-in, something that has rarely occurred. https://www.puc.texas.gov/consumer/facts/faq/Muni.aspx; https://quickelectricity.com/electricity-choice-in-texas-why-dont-all-texans-have-choice-in-electric-providers/.

successful electric market design, in terms of producing economically efficient outcomes. (I note that some industry observers, including myself, have questioned whether such a market design, which relies explicitly on the expectation of price spikes at times of power shortages is politically sustainable in the event that such conditions actually occur.[16])

- For several years, the North American Electric Reliability Corporation ("NERC") has pointed to the fact that ERCOT operates with slim reserve margins and with related potential reliability risks. As explained by James Robb, who leads NERC, in March 11th, 2021 testimony before the Senate Energy and Natural Resources Committee: "Concern for ERCOT's reserve margins has been a standing concern in NERC's assessments. In the most recent 2020/2021 Winter Reliability Assessment, NERC warns of the potential for extreme generation resource outages in ERCOT due to severe weather in winter and summer, and the potential need for grid operators to employ operating mitigations or energy emergency alerts to meet peak demand."[17]

- Although Texas is typically a summer-peaking system, with highest electrical demand during the hottest-weather months, it has previously experienced extreme cold weather conditions during the winter which created electric reliability problems when power plants were not able to perform, for one reason or another. During a cold snap that affected the Southwestern states (including Texas) in February 2011, for example: "Between February 1 and February 4, a total of 210 individual generating units within the footprint of [ERCOT] … experienced either an outage, a derate, or a failure to start. The loss of generation was severe enough on February 2 to trigger a controlled load shed of 4000 MW, which affected some 3.2 million customers."[18] ERCOT had thus experienced prior difficulties in maintaining reliable electricity service during extreme winter weather conditions.

- Following an investigation of that February 2011 cold-weather reliability event in the Southwest, the staffs of FERC and NERC made findings and recommendations that were relevant to actions of state legislators and regulators, owners of electric generating units, and parties in the natural gas industry in Texas.[19] The FERC/NERC report encouraged, among other things, that state policy

[16] "Although many economic experts in the electric industry point to the success of the ERCOT market design as a model that should be adopted and implemented in other regions, it is unlikely that that approach—with its mandatory retail competition and an energy-only centralized wholesale market—will be taken up in most (if any) other regions of the U.S." Susan Tierney, "Wholesale Power Market Design in a Future Low-Carbon Electric System: A Proposal for Consideration," November 28, 2020, at https://media.rff.org/documents/tierney-white-paper-on-wholesale-market-design-12-15-2020-final-to-wri-rff.pdf. Also, "Exporting the ERCOT model? It would surprise me if any other states can or choose to pursue it, even if it has been successful there. (And the jury is out about how well it would work with it is dominated by zero-emitting resources, rather than 64% fossil.)" Susan Tierney, "Wholesale Power Market Design in a Future Low-Carbon Electric System: A Proposal for Consideration," World Resources Institute/Resources for the Future Workshop on market designs for the clean energy transition, December 17, 2020, at https://media.rff.org/documents/tierney-wri-rff-market-design-workshop_-_12-17-2020_v2.pdf.

[17] James Robb, President and CEO of NERC, "Reliability, Resiliency, and Affordability of Electric Service in the United States Amid the Changing Energy Mix and Extreme Weather Events," testimony before the Senate Energy and Natural Resources Committee, March 11, 2021, at https://www.energy.senate.gov/services/files/EB1D7E02-BC93-4DFF-A6A9-002341DA34CF.

[18] Staffs of the Federal Energy Regulatory Commission and the North American Electric Reliability Corporation, "Report on Outages and Curtailments During the Southwest Cold Weather Event of February 1-5, 2011: Causes and Recommendations" (hereafter referred to as the "FERC/NERC Staff Report on 2011 Cold Weather Events"), https://www.ferc.gov/sites/default/files/2020-04/08-16-11-report.pdf.

[19] FERC/NERC Staff Report on 2011 Cold Weather Events.

makers adopt policies to encourage actions to ensure improved performance of power systems. These findings and recommendations included the following:

- Finding: "The lack of any state, regional or Reliability Standards that directly require generators to perform winterization left winter-readiness dependent on plant or corporate choices…."[20]
- Finding: "Generators were generally reactive as opposed to being proactive in their approach to winterization and preparedness. The single largest problem during the cold weather event was the freezing of instrumentation and equipment."[21]
- Recommendation: "Transmission Operators and Balancing Authorities should obtain from Generator Owner/Operators their forecasts of real output capability in advance of an anticipated severe weather event; the forecasts should take into account both the temperature beyond which the availability of the generating unit cannot be assumed, and the potential for natural gas curtailments."[22]
- Recommendation: "States in the Southwest should examine whether Generator/Operators ought to be required to submit winterization plans, and should consider enacting legislation where necessary and appropriate."[23]
- Recommendation: "Lawmakers in Texas and New Mexico, working with their state regulators and all sectors of the natural gas industry, should determine whether production shortages during extreme cold weather events can be effectively and economically mitigated through the adoption of minimum, uniform standards for the winterization of natural gas production and processing facilities."[24]

- In their release of the 2011 report, the FERC and NERC staffs said that the outages could have been avoided, and "that the purpose of the report was not to assign blame but to look at the causes of the outages and figure out the best ways to prevent them in the future."[25]
- For the most part, the electric industry and gas industry in Texas did not act on these recommendations, nor did regulators at the PUCT (for electric industry issues) or at the Texas Railroad Commission (for gas industry issues). As of the start of 2021, the power generation and gas production/delivery systems in Texas had not undergone the types of weatherization actions that could have enabled the provision of energy supply in the event of extreme winter temperature events.[26] Apparently, the owners of these power-generation and natural gas facilities were not

[20] FERC/NERC Staff Report on 2011 Cold Weather Events, page 196.
[21] FERC/NERC Staff Report on 2011 Cold Weather Events, page 196.
[22] FERC/NERC Staff Report on 2011 Cold Weather Events, page 202.
[23] FERC/NERC Staff Report on 2011 Cold Weather Events, page 203.
[24] FERC/NERC Staff Report on 2011 Cold Weather Events, page 214.
[25] J.P. Finlay, "FERC/NERC report outlines steps to avoid winter outages in Southwest," *S&P Global Market Intelligence, August 16, 2011, at* https://platform.marketintelligence.spglobal.com/web/client?auth=inherit&overridecdc=1&#news/article?KeyProductLinkType=2&id=13185142
[26] Molly Christian, Zack Hale and Ellie Potter, "Experts mull market, reliability rule changes amid Texas, regional outages," *S&P Global Market Intelligence*, February 16, 2021, at https://platform.marketintelligence.spglobal.com/web/client?auth=inherit&overridecdc=1&#news/article?KeyProductLinkType=2&id=62688009.

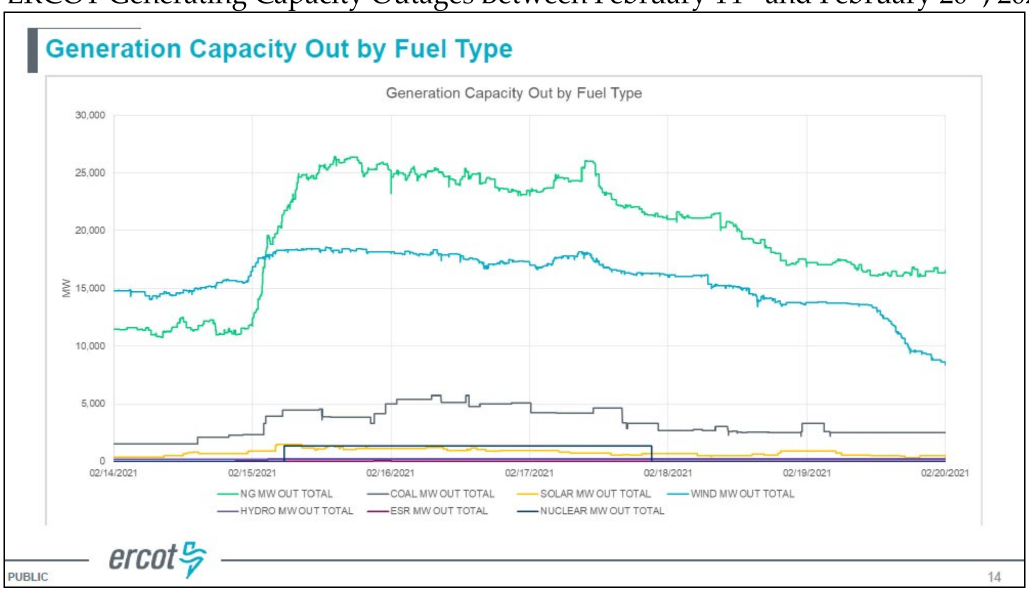
sufficiently incented by ERCOT Texas' market design to voluntarily put in place the physical equipment and/or contract agreements to enable them to be available to operate during shortage conditions.

- These—and other—conditions set the stage for the energy emergency events in February 2021.

What Happened: Real-time contributors to the Texas power outages

- During the second week of February 2021, extreme winter weather conditions affected the middle of the country, with frigid temperatures, snow and ice lasting for days. While other parts of that region routinely expect harsh conditions in the winter, Texas was particularly hard hit. Although ERCOT expected cold weather, the conditions were more extreme than anticipated.[27]
- In the ERCOT region, this weather produced record-breaking winter-time demand for electricity at the same time that various adverse conditions developed on the supply side.[28] From an electric-generating capacity point of view, power plant equipment froze, with over 48% of the region's total capacity unavailable at the highest point in the outages. All types of generating technologies experienced outages, with gas-fired capacity experiencing the highest amount of shut-down equipment (as shown in the ERCOT chart (Figure 1), below).

Figure 1:
ERCOT Generating Capacity Outages Between February 14th and February 20th, 2021[29]



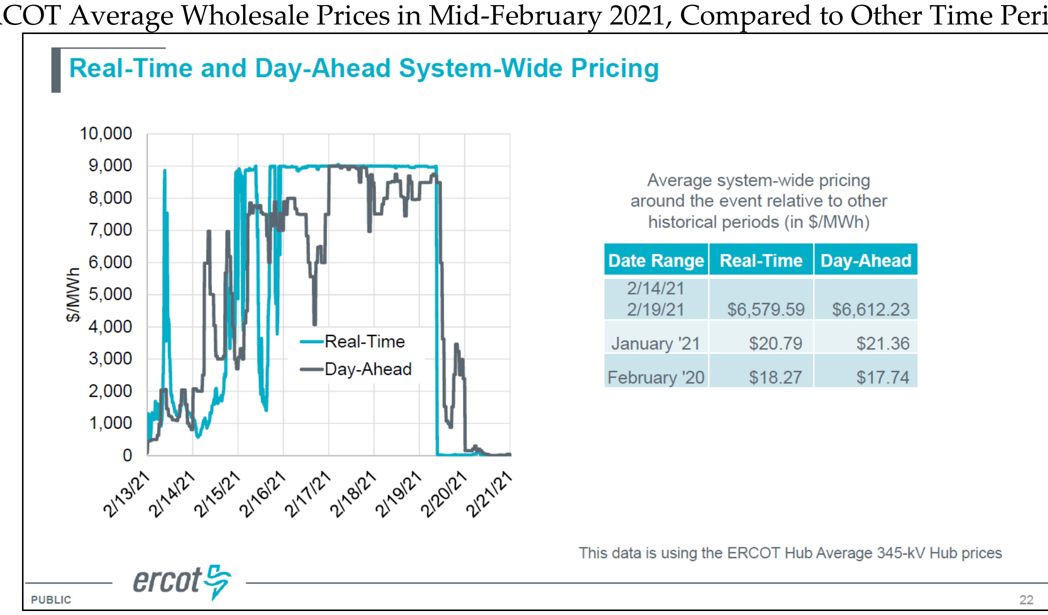
- From a fuel-supply point of view, natural gas became unavailable to significant numbers of power plants in ERCOT as gas wellheads and processing facilities froze up and as gas supply was

[27] ERCOT press release, "Extreme cold weather expected to result in record electric use in ERCOT region," February 11, 2021, at http://www.ercot.com/news/releases/show/224996.
[28] Bill Magness, "Review of February 2021 Extreme Cold Weather Event," ERCOT Presentation to Urgent ERCOT Board of Directors Meeting ERCOT, February 24, 2021 (hereafter "ERCOT 2-24-201 Presentation"), at http://www.ercot.com/content/wcm/key_documents_lists/225373/2.2_REVISED_ERCOT_Presentation.pdf.
[29] ERCOT 2-24-201 Presentation.

prioritized for home heating.[30] This led to price spikes in natural gas markets, with prices skyrocketing at points to 100 times their normal levels.[31]

- To avoid a catastrophic system-wide outage as potential demand exceeded available generation, ERCOT instituted rolling blackouts ("load shedding") to lower demand and move it to levels that could be met by generation. Such involuntary curtailments of electricity service extended over nearly three full days and at one point affected 20,000 MW of customer loads (compared to an estimated total demand of 76,819 MW in ERCOT, if power plant capacity and fuel supply had been in operation and all customer demand could have been met).[32]
- This led to enormous hardship for millions of people, including days when people did not have power during extremely cold weather and when many people also loss of water supply. Several dozen people died.[33]
- The human toll also played out (or will play out in the future) in many consumers' pocketbooks, as high prices in natural gas markets combined with the shortage conditions in power markets translated into extraordinarily high prices in wholesale power markets. During the Texas power crisis, wholesale electricity prices average averaging over $6,600 per MWh and at times rose to $9,000 per MWh, compared to average prices in January 2021 of $21 per MWh. (See Figure 2.)

Figure 2:
ERCOT Average Wholesale Prices in Mid-February 2021, Compared to Other Time Periods[34]



[30] Department of Energy, Emergency Situation Report, February 17, 2021, at https://www.energy.gov/sites/prod/files/2021/02/f82/TLP-WHITE_DOE%20Situation%20Update_Cold%20%20Winter%20Weather_%20Report%20%232%20FIN.pdf.
[31] ERCOT 2-24-201 Presentation; https://www.smith.senate.gov/us-senator-tina-smith-calls-investigation-including-possible-price-gouging-massive-natural-gas-0.
[32] ERCOT 2-24-201 Presentation.
[33] https://www.texastribune.org/2021/02/19/texas-power-outage-winter-storm-deaths/; https://www.texastribune.org/2021/02/19/texas-water-power-outages/.
[34] ERCOT 2-24-201 Presentation.

- From a retail electricity consumer's point of view, those wholesale prices would equate to $6.6 (or even up to $9.0) for every unit of electricity used during that period, if those electric costs were passed through in retail prices. One electric industry expert calculated that a large home heated by electricity in Texas would have paid $4,500 in high electric bills for that week alone if that household's electric service agreement allowed for pass through of costs in the wholesale market.[35]
- Although most small electricity consumers in Texas purchase electricity based on fixed prices, a small percentage of households do buy power through products where the Retail Electricity Provider may fully pass through costs in the wholesale market. Customers with such service agreements are now getting eye-popping bills. And consumers served by municipal and cooperative utilities will eventually end up paying for their utilities' higher costs from February.
- The ERCOT market monitor has calculated that decisions by the PUCT and ERCOT during the crisis led to approximately $16 billion in overpriced electricity, and recommended that the PUCT recalculate and revise prices and payments retroactively[36] — something that the PUCT has elected not to do.[37]
- Meanwhile, state and federal investigations are underway to examine the outages and whether any price manipulation may have occurred.[38]

Clearly, these recent events in Texas are a chilling reminder of the critical role that reliable and resilient electricity plays in providing basic needs and access to critical services to households, businesses and other electricity consumers.

Research needs to enhance reliability and resilience of the electric system

Although the Texas electricity crisis was an unusual event, to say the least, there are many observers who have pointed out that such events could happen elsewhere in the U.S., and that steps are needed to proactively prepare the electric system to lower the risks of such occurrences and to lessen their adverse impacts. Although Texas' winter weather in February 2021 was extraordinarily cold, and colder than expected, it is now predictable that extreme weather events will occur more frequently and be more intense as a result of climate change.[39]

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[35] Seth Blumsack, "What's behind $15,000 electricity bills in Texas?" The Conversation, February 24, 2021, at https://theconversation.com/whats-behind-15-000-electricity-bills-in-texas-155822 .

[36] Letter from Potomac Economics to the Chair of the Public Utility Commission of Texas, March 4, 2021, at https://interchange.puc.texas.gov/Documents/51812_61_1114183.PDF.

[37] Paul Ciampoli, "Texas PUC declines to take action in response to report on $16 billion in additional costs," March 8, 2021, at https://www.publicpower.org/periodical/article/texas-puc-declines-take-action-response-report-16-billion-additional-costs.

[38] For example: Federal Energy Regulatory Commission News Release, "FERC, NERC to Open Joint Inquiry into 2021 Gold Weather Grid Operations," February 16, 2021, at https://www.ferc.gov/news-events/news/ferc-nerc-open-joint-inquiry-2021-cold-weather-grid-operations; FERC News Release, "FERC to Examine Potential Wrongdoing in Markets During Recent Cold Snap," February 22, 2021, at https://www.ferc.gov/news-events/news/ferc-examine-potential-wrongdoing-markets-during-recent-cold-snap; Garrett Hering, "In the wake of the storm, Texas PUC opens probe into outages," S&P Global Market Intelligence, February 19, 2021, at https://platform.marketintelligence.spglobal.com/web/client?auth=inherit&overridecdc=1&#news/article?KeyProductLinkType=2&id=62768135.

[39] For example: Academies' 2017 Resiliency Report"), at https://doi.org/10.17226/24836; Government Accountability Office, "Electricity Grid Resilience: Climate Change Is Expected to Have Far-Reaching Effects and DOE and FERC Should Take Actions," March 2021, at https://www.gao.gov/products/gao-21-423t; and J.M Melillo, T.C. Richmond, and G.W. Yohe, *Climate Change Impacts in the United States: The Third National Climate Assessment*, U.S. Global Change Research Program, at https://doi:10.7930/J0Z31WJ2.

Further, it is well-established that electric system infrastructure (along with other energy infrastructure) is vulnerable to such extreme weather events, with potentially risks to and costly impacts on human lives, public health, and economic activity. As the National Academies' 2017 report on Enhancing the Resilience of the Electric Grid pointed out:

> Electricity and the underlying infrastructure for its production, transmission, and distribution are essential to the health and prosperity of all Americans. It is important to make investments that increase the reliability of the power system within reasonable cost constraints. However, the system is complex and vulnerable. Despite all best efforts, it is impossible to avoid occasional, potentially large outages caused by natural disasters or pernicious physical or cyber attacks. This report focuses on large-area, long-duration outages—considered herein as blackouts that last several days or longer and extend over multiple service areas or states. When such major electricity outages do occur, economic costs can tally in the billions of dollars and lives can be lost. Hence, there is a critical need to increase the resilience of the U.S. electric power transmission and distribution system—so that major outages are less frequent, their impacts on society are reduced, and recovery is more rapid—and to learn from these experiences so that performance in the future is better.[40]

As I noted previously, I was a member of the Committee that prepared that 2017 consensus report. We made a number of recommendations relating to the need for greater research and development to support grid resiliency, which I present below. I also provide (below) a number of research-related recommendations from "The Future of Electric Power in the United States" (2021), which is recent report from a different Academies' consensus committee on which I also served.[41]

While the latter report focused on a much broader set of issues than enhancing the resilience of the electric system, it included grid resilience as one of the five major needs for the future electric power system[42]:

1. Improve our understanding of how the system is evolving.
2. Ensure that electricity service remains clean and sustainable, and reliable and resilient.
3. Improve understanding of how people use electricity and sustain the "social compact" to keep electricity affordable and equitable in the face of profound technological changes.
4. Facilitate innovations in technology, policy and business models relevant to the power system.
5. Accelerate innovations in technology in the face of shifting global supply chains and the influx of disruptive technologies.

In the context of this Science Committee hearing, I call your attention in particular to the Academies' discussion and conclusion regarding the essential role of federal support for RD&D on electric system issues:

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[40] Academies' 2017 Resiliency Report (preface).

[41] These two committees were chaired by M. Granger Morgan of Carnegie Mellon University, and like Granger and myself, several other members of the Future of the Electric System Committee also served on the Resiliency Study: Anjan Bose of Washington State University; Terry Boston, of Terry Boston LLC; Jeffrey Dagle of the Pacific Northwest National Laboratory; William Sanders of Carnegie Mellon University; and David Victor of the University of California, San Diego.

[42] National Academies of Sciences, Engineering, and Medicine, *The Future of Electric Power in the United States*, 2021 (hereafter referred to as the "Academies' 2021 Electric Power Report"), pages 3-7, at https://doi.org/10.17226/25968.

> The Department of Energy (DOE) is the federal entity with a mission to focus on the *longer-term* issues of developing and promulgating technologies and strategies to increase the resilience and modernization of the electric grid. No other entity in the United States has the mission to support such work, which is critical as the electricity system goes through the transformational changes described in this report. The committee views research, development, and demonstration activities that support reliable and resilient electricity systems to constitute a public good. If funding is not provided by the federal government, the committee is concerned that this gap would not be filled either by states or by the private sector. In part this is because the challenges and solutions to ensuring grid resilience are complex, span state and even national boundaries, and occur on time scales that do not align with business models.[43]

In the rest of my testimony, I will excerpt parts of both Academies reports, with a focus on their findings and recommendations that address federally supported research needs for a secure and resilient grid.

The Academies' 2017 Resiliency Report had several major overarching recommendations related to these issues:

> **Overarching Recommendation 3:** However the Department of Energy chooses to organize its programs going forward, Congress and the Department of Energy leadership should sustain and expand the substantive areas of research, development, and demonstration that are now being undertaken by the Department of Energy's Office of Electricity Delivery and Energy Reliability and Office of Energy Efficiency and Renewable Energy, with respect to grid modernization and systems integration, with the explicit intention of improving the resilience of the U.S. power grid. Field demonstrations of physical and cyber improvements that could subsequently lead to widespread deployment are critically important. The Department of Energy should collaborate with parties in the private sector and in states and localities to jointly plan for and support such demonstrations. Department of Energy efforts should include engagement with key stakeholders in emergency response to build and disseminate best practices across the industry.[44]
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> **Overarching Recommendation 5:** The Department of Energy, together with the Department of Homeland Security, academic research teams, the national laboratories, and companies in the private sector, should carry out a program of research, development, and demonstration activities to improve the security and resilience of cyber monitoring and controls systems, including the following:
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> - Continuous collection of diverse (cyber and physical) sensor data;
> - Fusion of sensor data with other intelligence information to diagnose the cause of the impairment (cyber or physical);
> - Visualization techniques needed to allow operators and engineers to maintain situational awareness;

[43] Academies' 2017 Resiliency Report, page 4.
[44] Academies' 2017 Resiliency Report, page 135.

- Analytics (including machine learning, data mining, game theory, and other artificial intelligence-based techniques) to generate real-time recommendations for actions that should be taken in response to the diagnosed attacks, failures, or other impairments;
- Restoration of control system and power delivery functionality and cyber and physical operational data in response to the impairment; and
- Creation of post-event tools for detection, analysis, and restoration to complement event prevention tools.[45]

Additionally, the Academies' 2017 Resiliency Report includes more specific recommendations related to federally funded research needs for the nation's electric system:

Recommendation #1 to DOE: Improve understanding of customer and societal value associated with increased resilience and review and operationalize metrics for resilience by doing the following: Developing comprehensive studies to assess the value to customers of improved reliability and resilience (e.g., periodic rotating service) during large-area, long- duration blackouts as a function of key circumstances (e.g., duration, climatic conditions, societal function) and for different customer classes (e.g., residential, commercial, industrial) (Study Report Recommendation 2.1)

Recommendation #2 to DOE: Support research, development, and demonstration activities, as well as convening activities, to improve the resilience of power system operations and recovery by reducing barriers to adoption of innovative technologies and operational strategies. These include the following:

- Initiating and supporting ongoing research programs focused on the operation of degraded or damaged electricity systems, including supporting infrastructure and cyber monitoring and control systems, where key subsystems are designed and operated to sustain critical functionality. (Study Report Recommendation 4.6)
- Continuing to support research and development of advanced large power transformers, concentrating to conduct several demonstration projects. (Study Report Recommendation 6.7)

Recommendation #3 to DOE: Advance the safe and effective development of distributed energy resources ("DERs") and microgrids by doing the following:

- Initiating research, development, and demonstration activities to explore the extent to which DERs could be used to help prevent large-area outages. (Study Report Recommendation 4.2)
- Supporting demonstration and a training facility (or facilities) for future microgrids that will allow utility engineers and non-utility microgrid operators to gain hands-on experience with islanding, operating, and restoring feeders (including microgrids). (Study Report Recommendation 5.6)

[45] Academies' 2017 Resiliency Report, pages 135-136.

Recommendation #4 to DOE: Work to improve the ability to use computers, software, and simulation to research, plan, and operate the power system to increase resilience by doing the following:

- Collaborating with other research organizations, including the National Science Foundation, to expand support for interdisciplinary research to simulate events and model grid impacts and mitigation strategies. (Study Report Recommendation 4.3)
- Supporting and expanding research and development activities to create synthetic power grid physical and cyber infrastructure models. (Study Report Recommendation 4.4)
- Collaborating with other research organizations, including the National Science Foundation, to fund research on enhanced power system wide-area monitoring and control and the application of artificial intelligence to the power system. Such work should include how the human–computer interface and visualization could improve reliability and resilience. (Study Report Recommendation 4.8)
- Leading efforts to develop standardized data definitions, communication protocols, and industrial control system designs for the sharing of both physical and cyber system health information. (Study Report Recommendation 4.9)
- Developing a high-performance utility network simulator for use in cyber configuration and testing. (Study Report Recommendation 6.12)

Recommendation #5 to DOE: Work to improve the cyber-security and other cyber resilience of the grid by doing the following:

- Embarking on a research, development, and demonstration program that results in a prototypical cyber- physical-social control system architecture for resilient electric power systems. (Study Report Recommendation 4.10)
- Developing the ability to apply physics-based modeling to anomaly detection, which provides real-time or better physics models that derive optimal power flow and monitor performance for more accurate state estimation. (Study Report Recommendation 6.8)

The Academies' 2021 Electric Power Report explains the five needs of the nation's electric system which I listed above, and includes recommendations relating to each one:

Regarding the first need—#**1: Improving our understanding of how the system is evolving**—the report states that:

> Because of many parallel changes in technology, patterns of electricity consumption, and social expectations for electric power, it is more difficult to forecast future electricity supply, demand, and infrastructure today than it was a few decades ago. The tools for forecasting electric futures need to be capable of adaptation because the architecture of the grid will evolve in different ways in different regions, and will adjust as the country reduces emissions of greenhouse gases from the overall economy through decarbonizing the electric supply and more pervasive use of electricity. As part of this effort, the nation needs to build and test new tools for simulation and experimentation to

understand how the grid of the future will behave and how operators and policy makers can ensure its continued reliability.[46]

The Academies' 2021 Electric Power Report includes research recommendations related to improving our understanding of how the electric system is evolving:[47]

Recommendation 4.5: Government support for key electricity research initiatives such as grid modernization and development of technology necessary for deep decarbonization should be sustained for sufficient periods of time to enable new areas of discovery. Congress should appropriate multiyear (minimum of 5-year) funding streams for proposed initiatives in key areas of national interest such as those identified, and DOE should implement long-term funding for projects that demonstrate alignment with critical national needs, technical success, potential net economic benefits, and cost-shared funding where appropriate. Such programs should follow best practices that include ensuring that DOE program managers have the knowledge and authority to oversee projects effectively and efficiently and clear criteria to govern advancement of projects.

Recommendation 5.5: DOE should support a sustained collaboration of national labs, academia, utilities, and vendors to develop a family of intercompatible simulation tools that have common standard interfaces to work together to assess the performance of the present grids and better anticipate the implications of the various ways the grid architectures may evolve in the future. As having a single large integrated model of very large, complex grids is impractical, the development and standardization of common interfaces between simulation tools will enable the studies of evolving architectures of generation, transmission, distribution, and ICT.

Recommendation 5.8: Because there will always be limits to what can be learned through simulation, DOE should choose the most promising new architectures indicated by large scale simulation studies in order to identify and plan a number of large-scale field experiments that could verify the advantages of such grid architectures under actual operations. Such field experiments of grid architecture would be qualitatively and quantitatively much larger in scope than the usual prototyping of a component such as a storage device, and should be reserved for when adequate resources and opportunities are available.

Recommendation 6.2: Owing to the increasing importance of computing, communications, and control technologies for the operation of the current and future grid, Congress should appropriate funds to the National Science Foundation, in consultation with DOE, to specifically focus on research programs exploring the implications and applications of rapidly evolving computing, communications, and control technologies on grid cybersecurity and cyber resiliency.

Regarding the second need for the future electric system—#**2: Ensuring that electricity service remains clean and sustainable, and reliable and resilient**—the Academies' 2021 Electric Power Report states that:

Reducing emissions of CO_2 and other environmental impacts of electricity generation will remain a major challenge in the coming decades. While the focus of the role of electricity generation on

[46] Academies' 2021 Electric Power Report, page 3.
[47] Academies' 2021 Electric Power Report. These recommendations (with their numbering reflecting the chapter in which they appear) are summarized on pages 8-9 of the report, with related discussion and findings found in chapters 4, 5 and 6 of the report.

ambient air quality may diminish as generation becomes less polluting, there is a growing focus on increasing sustainability and addressing climate change, in part through increased use of renewables. At high penetrations, this will require increasing the capacity of high-voltage, multistate transmission networks. The balance between reliability and resilience may shift over time but excellent overall performance will remain essential. The power system is vulnerable to a variety of natural events and accidental as well as pernicious human physical and cyber-attacks that can be minimized yet not eliminated entirely. New technologies, along with continued investment in critical elements of the electric power system, such as long-distance transmission and robust distributed resources, will improve the nation's capabilities. The nation, the electric industry and other stakeholders need to do a better job of educating and training people at all levels to design, reinforce, manage, and run a resilient and effective electric system.

The Academies' 2021 Electric Power Report includes research recommendations related to the need to ensure that electricity service remains clean and sustainable, and reliable and resilient:[48]

Recommendation 4.7: Given the structural, technological, economic, and operational changes under way in so many regions of the U.S. electric industry, it will be important for the federal government to fund and support research and analysis to help mitigate operational and planning uncertainties. DOE should sponsor research that will enhance the temporal flexibility of net electricity demand and enhance other services vital to grid reliability through pricing or other mechanisms. This will be important for supporting the entry of resources and services that can meet states' and consumers' desires for low-carbon electricity supply.

Recommendation 5.1: To meet the challenge of dramatically lowering U.S. CO_2 emissions, DOE, EPRI, universities, and industry should focus on developing: generation technologies with zero direct CO_2 emissions, low- carbon technologies with high dispatchability and fast ramping capabilities, storage systems for multihour, multiday and seasonal time-shifting; and power electronics to enable real-time control of the grid.

Recommendation 6.1: DOE's research program in grid cybersecurity is an important source of innovation to improve the resiliency of future grid infrastructure and operations. DOE should develop a regularly updated R&D priority roadmap in collaboration with the electric industry with input from academic and national lab researchers, and the vendor community. The R&D priorities in the roadmap should be funded by appropriations from Congress to DOE. The roadmap should be oriented to develop and demonstrate new technologies for resilient architectures that will enable energy delivery systems, and any interconnected systems, to be designed, installed, operated, and maintained to survive a cyber incident while sustaining critical functionality and enabling quick recovery.

Regarding the third need for the future electric system—#**3: Improving understanding of how people use electricity and sustain the "social compact" to keep electricity affordable and equitable in the face of profound technological changes**—the Academies' 2021 Electric Power Report states that:

Already many changes in the grid reveal opportunities for new services and configurations of electric resources. Some kinds of profound changes in electric supply, such as some customers

[48] Academies' 2021 Electric Power Report. These recommendations are summarized on pages 9-13 of the report, with related discussion and findings found in chapters 4, 5 and 6 of the report.

> becoming less dependent on grid- delivered power, could be highly disruptive to the social compact that has been central to the electric power industry and its provision of universal service for over a century. These changes could have large impacts on customers with low incomes. It is crucial to build tools to understand those needs along with devising regulatory responses to evolve and selectively strengthen social compacts in light of changing circumstances.

The Academies' 2017 Electric Power Report includes a research-related recommendation relevant to the need to improve our understanding of how keep electricity affordable and equitable in the face of profound technological changes third need for the future power system is:[49]

> **Recommendation 4.9:** The increase in government funding identified in Recommendation 4.8 [relating to substantial increases in federal RD&D for the electric section, as discussed below under the discussion of the fifth need for the future power system] should include areas that have traditionally been neglected yet are vitally important to the future of the electric power system. Those include research to support planning, design, operation and control of grid systems as they face new challenges such as deep decarbonization and the need for resiliency against natural, manmade and cyber hazards. The consortium and multiyear approach of the Grid Modernization Initiative is a good model but must be funded reliably. Other traditionally neglected areas of research include the social science needed to inform policy and technology development.

Regarding the fourth need for the future electric system—#**4: Facilitating innovations in technology, policy and business models relevant to the power system**—the Academies' 2017 Electric Power Report states that:

> New technologies, such as clean generation, wide electrification, energy storage, power electronics, and systems for monitoring and control, can enable large changes in the way the power system is organized and operated. Especially large changes may occur in the distribution and retail parts of the grid where the system meets people and non-utility companies (the so-called grid edge"). While supply provided by central generation and transmission and distribution wires will remain essential, technical, policy and business-model changes could speed innovation and the introduction of new services to consumers at the grid edge. Understanding how electricity consumers behave, and how devices and energy services can be aggregated for supply, and how such trends affect system loads is emerging as one of most profound technological, regulatory and planning challenges and opportunities facing the future of the grid. That understanding requires situational awareness and control across potentially tens of millions of nodes and at high rates of response (milliseconds, not seconds). Such changes will require flexible system planning and operations at both the bulk-power and local levels.

The research-related recommendations related to the need to facilitate innovations in technology, policy and business models relevant to the power system include:[50]

> **Recommendation 3.6:** With support from Congress and state legislatures**,** DOE, state energy research organizations, and foundations should provide support for social science research

[49] Academies' 2021 Electric Power Report. These recommendation is summarized on page 13 of the report, with related discussion and findings found in chapter 4 of the report.
[50] Academies' 2021 Electric Power Report. These recommendations are summarized on pages 8-9 of the report, with related discussion and findings found in chapters 4, 5 and 6 of the report.

> and regulatory/policy analysis designed to identify and assess alternative models for regulation, innovation and industry structure in the retail/ distribution segment of the electric system. Such research and analysis efforts should also address opportunities and mechanisms to allow for flexible demand and the value of doing so for electric system performance, cost, and emissions. Such research and analysis should also focus on the development and assessment of metrics to measure how infrastructure investment decisions and authorized actions would affect carbon emissions. Such work should involve and be informed by industry, researchers at universities, think tanks and/or the national labs, and/or other institutions with research programs in the following fields (as well as others): energy economics, behavioral economics, public policy analysis, law, finance, and utility regulation.
>
> **Recommendation 4.6:** Greater deployment of advanced electrical technology is essential and will require expanded support for DOE-backed demonstration projects, including through loan programs and support for industrial consortia that deploy critical technologies. Such expanded support should follow best practices in the implementation of technology demonstration and deployment programs. Programs should be designed for rapid learning (and course corrections where needed) and periodic assessment of the overall portfolio for its performance. Proposals for funded projects should include a clear articulation of how a demonstration could be commercialized including a budget for such activities—so that a larger fraction of successful demonstration projects lead to wider deployment.

Regarding the fifth need for the future electric system—#**5: Accelerating innovations in technology in the face of shifting global supply chains and the influx of disruptive technologies**—the Committee report states that:

> Many of the basic power system technologies were first developed in the United States. However, the supply chains and manufacturing for most critical electric power system technologies have now moved offshore. The United States has been underinvesting in the innovation needed for future electric system performance. Massive new private and public investments are needed in innovation, especially for more cutting-edge technologies on which the future grid will depend. Policies are needed to move supply chains and manufacturing for those technologies back to the United States, while recognizing that innovation and manufacturing are now global. The United States must balance competing goals—one to gain from the advantages of a global search for innovative solutions and the other to ensure U.S. control and awareness of and access to critical grid infrastructure technologies. The advantages of engagement and awareness of progress overseas will be particularly important where grids are expanding in size and function, which facilitates testing, demonstration, and deployment of new technology.

Research-related recommendations related to the need to accelerate innovations in technology in the face of shifting global supply chains and the influx of disruptive technologies include:[51]

> **Recommendation 4.8:** In order to meet the challenge of serving all Americans with safe, clean, affordable, reliable and resilient electric power in a rapidly changing environment, while building a stronger U.S. industrial base that can advance those goals, Congress should increase substantially

[51] Academies' 2021 Electric Power Report. These recommendations (with their numbering reflecting the chapter in which they appear) are summarized on pages 8-9 of the report, with related discussion and findings found in chapters 4, 5 and 6 of the report.

the overall level of support for RD&D on the production, delivery and use of electric power. Increasing such support too rapidly would lead to inefficiency and waste. This sets an upper bound on the rate and amount of increase. Over the next decade, support for basic science that is broadly related to electric power should be doubled, and support for applied development and demonstration related to electric power should be tripled.

Recommendation 5.2: The United States has lost ground in the manufacturing of conventional grid-scale power control technologies (e.g., HVDC and FACTS) and is deploying very little of these advanced solutions. Developments in rapidly growing technologies, such as PV, wind, EV, and energy storage, suggest a new paradigm may be rapidly emerging which is more modular, distributed and edge- intelligent, and which may be able to compete with and outperform the existing grid paradigm in terms of sustainability, reliability, resilience, and affordability. A rapidly changing paradigm for electrical power and the grid offer a unique opportunity for U.S. research and manufacturing to reclaim their global lead in this critical area. DOE, EPRI, other domestic and international research organizations, universities, and world-wide industry should identify such "breakaway" threads early, work with industry, investors and regulators to understand potential roadmap and impact. Then DOE, EPRI, and industry should collaborate to develop and fund a research agenda that creates fast-moving programs that help de-risk such solutions from technology, market and regulatory perspectives.

Conclusion

I hope that the Committee considers my testimony as it determines how the federal research agenda and programs might provide much-needed and valuable greater support for research in support of a secure and resilient electric system in the U.S.

Thank you for affording me this opportunity to present this information and my opinions to the Committee.

Bio of Susan F. Tierney, Ph.D.

I am a Senior Advisor at Analysis Group, an economic consulting firm headquartered in Boston, with other U.S. offices in California, Colorado, Illinois, New York, Texas, and Washington, D.C., and with international offices in Europe and Asia.

I have been involved in issues related to public utilities, ratemaking and electric industry regulation, electric system reliability and resilience, and energy and environmental economics and policy for over 35 years. During this period, I have worked on electric and gas industry issues as a utility regulator and energy/environmental policy maker, consultant, academic, and expert witness. I have been a consultant and advisor to private and publicly owned energy companies, grid operators, government agencies, large and small energy consumers, environmental organizations, foundations, Indian tribes, and other organizations on a variety of economic and policy issues in the energy sector.

Before becoming a consultant, I held several senior governmental policy positions in state and federal government, having been appointed by elected executives from both political parties. I served as the Assistant Secretary for Policy at the U.S. Department of Energy. I held senior positions in the Massachusetts state government as Secretary of Environmental Affairs; Commissioner of the Department of Public Utilities; Executive Director of the Energy Facilities Siting Council; and chair of the Board of the Massachusetts Water Resources Authority.

My Masters degree and Ph.D. in regional planning are from Cornell University. I previously taught at the University of California at Irvine and at MIT. I am a member of the advisory councils at Columbia University's Center for Global Energy Policy, New York University's Institute for Policy Integrity, and Duke University's Nicholas School for the Environment.

I currently sit on several non-profit boards and commissions, including as: chair of the boards of ClimateWorks Foundation and of Resources for the Future; a trustee of the Barr Foundation; and a director of World Resources Institute and of the Energy Foundation. I am currently a member of two Committees of the National Academies of Sciences, Engineering, and Medicine: the Committee on Accelerating the Decarbonization of the U.S. Energy System; and the Committee on the Future of Electric Power in the United States. I chair the National Renewable Energy Laboratory's External Advisory Council; I previously chaired the U.S. Department of Energy's Electricity Advisory Committee, and was a member of the National Academy of Sciences committee on resiliency of the U.S. electric system. I serve on the NYISO's Environmental Advisory Council. I was co-lead convening author of the Energy Supply and Use chapter of the Third National Climate Assessment. I previously served on the Secretary of Energy's Advisory Board, and chaired the Policy Subgroup of the National Petroleum Council's study of the North American natural gas and oil resource base.

After 35 years in Boston, I moved with my husband to his home state of Colorado in 2016.